

Evidence Report:

Risk of Performance Errors Due to Training Deficiencies

Human Research Program Space Human Factors and Habitability Element

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I. PDR Risk Title: Risk of Performance Errors Due to Training Deficiencies

Risk Statement: *Given that existing training methods and paradigms may inadequately prepare long-duration, autonomous crews to execute their mission, there is a risk that increased flight and ground crew errors and inefficiencies, failed mission and program objectives, and increased crew injuries will occur.*

The Risk of Performance Errors Due to Training Deficiencies is identified by the National Aeronautics and Space Administration (NASA) Human Research Program (HRP) as a recognized risk to human health and performance in space. The HRP Program Requirements Document (PRD) defines these risks. This Evidence Report provides a summary of the evidence that has been used to identify and characterize this risk.

The Risk of Performance Errors Due to Training Deficiencies (TRAIN) is one of five Space Human Factors Engineering (SHFE) risks within the Space Human Factors and Habitability (SHFH) Element. The other risks are: the Risk of Inadequate Mission, Process and Task Design (MPTASK), the Risk of Inadequate Design of Human and Automation / Robotic Integration (HARI), the Risk of Inadequate Human-Computer Interaction (HCI), and the Risk of Incompatible Vehicle/Habitat Design (HAB). Each of these risks has an evidence report and research plan within HRP (see <http://humanresearchroadmap.nasa.gov/>).

Research gaps in all of these risk areas are primarily focused on the challenges of Exploration missions, i.e., beyond Low Earth Orbit (LEO). Ground laboratories, analogs, and ISS are used to answer research questions necessary to ensure that future Exploration crew members and ground support personnel, who will be dealing with many unknowns, communication delays, increasing autonomy, and limited (or no) resupply will be able to adequately perform their tasks and successfully and safely complete their missions.

SHFE risks are also the critical components of a single human factors risk accepted and managed by the NASA Human-System Risk Board (HSRB) – the Risk of Reduced Crew Performance due to Inadequate Human-System Interaction Design (HSID). This risk was established to ensure that the appropriate level of human-centered design, development, and research is undertaken for Exploration class space vehicles. The risk statement is shown below:

Risk of Reduced Crew Performance due to Inadequate Human-System Interaction Design (HSID):

Given the criticality of human-systems interaction during long duration spaceflight operations with increasing autonomy and time delay, there is a possibility of reduced crew performance due to inadequate human-system interaction design that may result in-flight and ground errors, impacts to timeline, failure to accomplish critical tasks, failed mission objectives, and an increase in crew injuries.

II. Executive Summary

Substantial evidence supports the claim that inadequate training leads to performance errors. Barshi and Loukopoulos (2012) demonstrate that even a task as carefully developed and refined over many years as operating an aircraft can be significantly improved by a systematic analysis, followed by improved procedures and improved training (see also Loukopoulos, Dismukes, & Barshi, 2009a). Unfortunately, such a systematic analysis of training needs rarely occurs during the preliminary design phase, when modifications are most feasible. Training is often seen as a way to compensate for deficiencies in task and system design, which in turn increases the training load. As a result, task performance often suffers, and with it, the operators suffer and so does the mission. On the other hand, effective training can indeed compensate for such design deficiencies, and can even go beyond to compensate for failures of our imagination to anticipate all that might be needed when we send our crew members to go where no one else has gone before.

Much of the research literature on training is motivated by current training practices aimed at current training needs. Although there is some experience with operations in extreme environments on Earth, there is no experience with long-duration space missions where crews must practice semi-autonomous operations, where ground support must accommodate significant communication delays, and where so little is known about the environment. Thus, we must develop robust methodologies and tools to prepare our crews for the unknown. The research necessary to support such an endeavor does not currently exist, but existing research does reveal general challenges that are relevant to long-duration, high-autonomy missions.

The evidence presented here describes issues related to the risk of performance errors due to training deficiencies. Contributing factors regarding training deficiencies may pertain to organizational process and training programs for spaceflight, such as when training programs are inadequate or unavailable. Furthermore, failure to match between tasks on the one hand, and learning and memory abilities on the other hand is a contributing factor, especially when individuals' relative efficiency with which new information is acquired, and adjustments made in behavior or thinking, are inconsistent with mission demands. Thus, if training deficiencies are present, the likelihood of errors or of the inability to successfully complete a task increases. What's more, the overall risk to the crew, the vehicle, and the mission increases.

III. Introduction

A. Risk Statement

Given that existing training methods and paradigms may inadequately prepare long-duration, autonomous crews to execute their mission, there is a risk that increased flight and ground crew errors and inefficiencies, failed mission and program objectives, and increased crew injuries will occur.

B. Risk Overview

The Risk of Performance Errors Due to Training Deficiencies relates to the systematic analysis, design, development, implementation, and evaluation of an effective spaceflight training program.

NASA has substantial experience in training astronaut crew members for space missions. Over 30 years of Space Shuttle missions and almost 15 years of missions to the International Space Station (ISS) stand as testimony for the success of NASA's training program for its astronauts. Unfortunately, this experience may not apply to future long-duration deep-space Exploration Class missions.

Shuttle astronauts spent several years in training prior to being assigned to a space mission, and then spent at least 18 months in training for their specific mission. That training included multiple rehearsals of the mission, which was scripted down to the minute. Training for a Shuttle mission involved at least 26 days of training for each day of mission, and the mission started shortly after the end of training. It didn't take long from launch to orbit. And then the mission was closely followed by Mission Control which provided continuous real-time support from the ground.

Space Station astronauts also spend several years in training prior to being assigned to a space flight, and then spend 30 months in training for their specific mission. Because the schedule on the Station is not nearly as intensive as it was on the Shuttle, Station astronauts only spend about 10 days of training for every day of mission, and missions start shortly after the end of training. It doesn't take long from launch to the ISS. And they too are closely followed by Mission Control which continues to provide continuous real-time support from the ground. If an unexpected malfunction occurs on board the ISS, a "cast of thousands" on the ground springs to action. New procedures are developed and tested, new parts can be sent on a relatively short order, and in some cases newly trained crew members can be sent as well. Mission Control can guide every action the on-board crew must take, and can monitor and control all on-board systems.

The people of Mission Control, NASA's flight controllers, are an experienced group. They have worked many missions and managed to solve many unexpected problems that have come up during the operation of ISS. Also, many of the crew members on board the ISS are astronauts with prior space flight experience either on Shuttle, or on the Station itself. And in both groups, the astronaut corps and the flight controller corps, there are many individuals with extensive mission experience and thorough knowledge of systems and operations.

Future missions will not be able to capitalize on the experiences developed during previous or current programs.

NASA's schedule includes a big gap between the expected retirement of the ISS and the start of the next mission. It's likely that both crew members and Flight Controllers involved in that next mission will have had no prior space flight experience. NASA's current Design Reference Missions (DRMs) call for a year-long mission to an asteroid and a mission to Mars that is likely to take approximately 32 months. Even at the ISS training-to-mission ratio of 10 to 1, it is not

practical to expect a crew assigned to a 32-months mission to be able to train for 320 months prior to their mission. In addition, major elements of the mission such as surface operations and return to Earth will only take place long after launch. Crews will spend substantial amounts of time in transit. What's more, communication delays will substantially curtail Mission Control's ability to provide continuous support from the ground, and real-time communication will not be possible. Similarly, sending spare parts from Earth will not be an option, let alone sending replacement crew members.

Thus, training astronauts for future space missions must be qualitatively different from current training paradigms and practices. As a result, the research conducted under the Training Risk is aimed at characterizing, quantifying and understanding what that difference is, and at how future astronauts should be trained.

The Training Continuum

Spaceflight training can be seen as distributed along a continuum, from initial pre-mission training, through ground and in flight refreshers, to onboard initial training, to just-in-time training, and all the way to performance support tools. For optimal results, careful distribution of training topics and training methodologies is required across the full continuum of training opportunities. The relevant issues at each point along this continuum are different. For the initial, pre-mission training, key questions have to do with task-based training vs. skill-based training, with optimal use of simulation facilities and the methodology by which the right level of simulation fidelity can be selected given the operational context and the individual learner, as well as the right training methodology and delivery system (e.g., classroom vs. computer based training (CBT)).

Onboard initial and refresher training will be significantly constrained by onboard delivery technologies, though virtual environments hold great promise. However, given the limited ground-based experience that has been gained thus far with such systems, key questions about training methodologies and delivery mechanisms remain, as well as about differences in acquisition and retention between on-ground and onboard training sessions. For refresher training in particular, questions about which topic should be refreshed and at what interval require a systematic methodology for determination. Just-in-time training requires the ability to expect the unexpected. That is, training can only be developed for expected tasks and situations. Just-in-time training will be needed for low likelihood events and situations that are not time critical. Because not all such events can be anticipated in advance, methods for the crew to develop their own training for such occasions must be developed for cases when communication delays prevent the up-link of such training from the ground.

Somewhat similar issues exist for the development of performance support tools, either for situations that don't justify training, or for when time is critical (including emergencies) and the crew does not have the opportunity to receive training prior to operations. Again, determining which events can be handled using performance support tools and how such tools can best be designed requires systematic methodologies that do not yet exist.

Performance Errors

Deficiencies in training programs can lead to a high risk of performance errors. Human error has been implicated as a causal factor in nearly two thirds of mishaps across NASA (Chandler, 2007), and similar situations exist in related domains like commercial and military aviation (70-80% of incidents and accidents involve human error directly, and 100% of accidents and incidents involve human limitations in some way, see, e.g., Maurino, Reason, Johnson, & Lee, 1995). In a significant proportion of incidents involving human error, incorrect procedure execution played a role.

Procedure execution errors (both of omission and commission) result from some combination of: inadequately designed tasks; inadequately designed procedures or tools; incomplete, inaccurate, or difficult-to-use documentation; fatigue, stress, injury, or illness; insufficient training (including lack of training for unanticipated operations); degradation of trained skills or knowledge; or inadequate understanding of the operational environment.

Historically, spaceflight operations have mitigated the risk of procedure execution errors in at least two ways: specially-trained crew members are assigned to missions and/or rotated into the operational environment when complex, mission-critical tasks must be performed; and, execution of such procedures is closely monitored and supported by flight controllers on the ground who have access to a broader and deeper pool of information and expertise than any individual operator. These mitigation factors apply well to long-duration missions in low earth orbit (LEO), such as operations on the ISS, and even lunar operations, as the communication delays are small and there is the ability to rotate or return crew members to Earth within a very short time.

However, emerging mission architectures include long-duration operations in deep space. Such operations do not allow for assignment of new crew members or even for the development and validation of new training on the ground. Further, delays in communication will have a disruptive effect on the ability of earth-based flight controllers to monitor and support space operations in real time. Therefore, given that historic risk mitigation factors do not support deep space operations, it is necessary to develop an understanding of how training can be tailored to better support long-duration deep space operations (including the extent to which materials, procedures, and schedules of training should be changed from current practices).

Likelihood and Consequences

Risk is always a function of likelihood and consequence. Two important considerations in assessing the likelihood of the Training Risk are mission duration and the extent to which the crew must be autonomous (due to communications lag). In addition, the likelihood is a function of the number of tasks that need to be performed and for which training is required. Thus, the likelihood of an error increases as the number of tasks increases. The likelihood of an error also increases with mission duration due to increased intervals between training and operation where no refresher or just-in-time training is in place; also, unexpected or emergent situations for which no applicable training exists are more likely in a long-duration mission. Likelihood also increases with increased levels of crew autonomy (due to minimal opportunity to obtain guidance/refresher

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training from ground support). When both of these factors are present (long-duration missions that require high crew autonomy), the likelihood of an adverse outcome is at its maximum. Accordingly, the Asteroid (Near Earth Asteroid (NEA)/Near Earth Object (NEO)) mission architecture (12+ month duration; up to 30 second communication delay) and the Mars mission architecture (3 year duration; up to 22 minute communication delay) are more likely to produce adverse outcomes than LEO missions. Lunar and ISS missions may have moderate to long-duration missions, but no appreciable communication delay; therefore, crew autonomy may not be a critical issue.

On the consequence side of the risk function, for missions where communication with ground support is fast and reliable and where rotation of crew into operations is possible, training can be made effective (in terms of length of time required for the acquisition of new knowledge and skills, durability of the acquired skills, and the ability to transfer learned knowledge and skills to new situations). Furthermore, it's possible to compensate for inadequate training utilizing current training practices: Ground support personnel can monitor operations in real-time and offer guidance, instruction, or other information. Freshly-trained crew can be provided from the ground to execute sensitive and/or complex operations, and those operations can be executed in close temporal proximity to extensive ground-based training. However, when crews are remote from Earth and communication involves delays or is unreliable, those augmentations and mitigations to training are not possible. If inadequate crew training results in tasks being executed incompletely, incorrectly, or inefficiently, operations will be hindered. Only delayed ground support will be available to assist with development of workarounds or to provide guidance, instruction, or other information required to correctly complete a deferred task, by which time it might be too late.

Long-duration deep-space missions also make the attenuation of adverse outcomes (particularly, re-supply or rescue operations) difficult or impossible, so the severity of outcomes are likely to increase for such operations. In general though, training-related errors are highly likely to cause time losses or inefficiencies, as well as loss of some mission objectives, and are less likely, but definitely able, to cause serious damage to vehicles, habitats, or other equipment. In some cases (and, as is often the case -- in combination with other factors), such errors could have significant impacts on mission success, and on vehicle and crew health and safety.

By themselves, most training inadequacies will lead to moderate impacts to operations (e.g., extended task times and the need for additional help from other crew or ground). Note that consequences become potentially far more serious in dynamic flight phases such as launch, docking, and landing, when there is very little time available to correct mistakes. It is also possible that a seemingly minor misstep during a medical operation would have personnel and health consequences; such consequences would be hard to predict. Similarly, a skipped procedural step might have dire consequences in an emergency procedure where time is critical. Given the autonomous nature of missions with communication delays, or even complete lack of communication, such cases of medical or vehicle emergencies are much more critical in an Exploration mission than in an ISS, or short duration missions.

Contributing Factors

The risk of performance errors due to training deficiencies includes two primary contributing factors: 1) Organizational Training Issues/Programs and 2) Matching Between Tasks and Learning and Memory Abilities. The contributing factors were derived from the Department of Defense (DoD) Human Factors Analysis and Classification System (HFACS), the industry standard for human error categorization (DoD, 2005). The evidence about risk reduction presented in this report is organized around two types of causal risk factors, selected from the HFACS categories of error (Shappell & Wiegmann, 2000). This classification system attempts to identify the point or points in which errors occurred in a causal chain of events that produced an accident.

1. Contributing Factor 1: Organizational Training Issues/Programs

Organizational training issues/programs is a factor when training programs are inadequate in design, development, or implementation (e.g. inappropriate or missing content, improper timing of training, poor or missing intervals of refresher training, mismatched training and operational environments) or when training programs are unavailable (e.g. unplanned need for immediate training in response to an unexpected hardware malfunction, unexpected injury to a crew member, or unexpected change in mission).

2. Contributing Factor 2: Matching Between Task and Learning and Memory Abilities

Matching between task and learning and memory abilities is another contributing factor. A mismatch can occur when the individual's knowledge acquisition strategies and predispositions are inconsistent with mission demands. Learning, namely the relative efficiency with which an individual acquires new information and with which the relatively permanent adjustments in behavior or thinking are made, may not be consistent with mission demands.

Thus, if training deficiencies are present, the likelihood of errors or of the inability to successfully complete a task increases. Importantly, there is an increase in the overall risk to the crew, the vehicle, and the mission.

C. Dependencies and Interrelationships with Other Risks

The Risk of Performance Errors Due to Training Deficiencies is related to risks in four of the five HRP Elements: Behavioral Health and Performance (BHP), Exploration Medical Capability (ExMC), Human Health Counter Measures (HHC), and SHFH.

Training is the systematic acquisition of knowledge, skills, and attitudes, and it is a necessary design component to any complex operation. It is about providing those being trained with the right competencies necessary to successfully perform a specific job or task (Salas, Wilson, Priest, & Guthrie, 2006). When the right knowledge is not transferred during training or not refreshed as needed, risk is introduced and errors can occur. Many HRP risks depend upon adequate training as a mitigation strategy.

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Separately, when hardware and software components are not designed well or teams selected do not work well together, these design and selection flaws can be seen in training. However, by the time training feedback regarding interfaces, tasks, operations and/or team dynamics is received, often hardware, system and software designs are relatively mature. It is often cost prohibitive to modify hardware design, or politically unfeasible to modify team selection based on feedback from training. Hence, designers must consider training when designing hardware and software with crew interfaces, procedures, and operations, and committees must consider individual's abilities and team dynamics when selecting crew. Using training to mitigate poor design or team selection can be very expensive and inefficient and should only be used as a last resort.

Incorporating training considerations in system design and designing effective training can go a long way towards mitigating mission risks. Several examples of the dependencies and interrelationships between training and other HRP risks are given below.

Dependencies with BHP

BHP conducts and supports research to reduce the likelihood and consequence of three human health risks: 1) The Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders ("Bmed Risk"); 2) The Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team ("Team Risk"); and 3) The Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload ("Sleep Risk"). Research studies across these three risk areas identify where gaps in mitigation may exist when considering the demanding needs of an Exploration mission. Strategically planned laboratory, field, and, when appropriate, flight investigations yield operationally relevant deliverables, including preventative and treatment countermeasures. In many instances, current operations can also benefit from these deliverables.

One specific area in which the need for additional countermeasures has been identified is that of training for team communication. Analyses of incident and accident reports have shown that inadequate communication between the ground and crew can cause frustration and can adversely affect performance. This deficient communication can be due to ground operators having difficulty identifying information related to task duration, which in turn frustrates the crew and ground personnel because the perception of task duration is different between those developing timelines and those executing the task. Many times crew members have not been able to identify information regarding what the ground could assist with, and what tasks could be automated to facilitate crew productivity (Rando, Baggerman, & Duvall, 2005). The most efficient and effective teams (e.g., aviation, military, design teams) manage to coordinate their activities with just enough, but not too much communication (Entin & Serfaty, 1999; Orasanu & Fischer, 1992; Patrashkova-Volzdoska, McComb, Green, & Compton, 2003). A team is at risk in the absence of task-specific procedures and appropriate communication training, especially for distributed teams in which shared context and location cannot carry some of the communication function. To overcome this risk, task procedures, training, and tools must be designed in such a way that essential information is communicated while keeping down the process cost, thereby minimizing the added workload required to communicate among team members. Communication skills training is subsumed under the broader umbrella of team skills training, which includes skillsets

such as task coordination, team adaptation, and self-maintenance. Communication skills facilitate each of these team behaviors, and consequently supports team performance. Team Dimensional Training's (TDT) guided debriefs, incorporated into NASA's Spaceflight Resource Management (SFRM) training, specifically focuses attention on the team skills of leadership/followership, supporting behaviors, in addition to communication delivery and information exchange. TDT has reduced tactical errors and improved decision making in military teams and has reduced flight controller certification training time (Bedwell, Smith-Jentsch, Sierra, & Salas, 2012). Additional information related to this topic can be found in the Evidence Book chapter for the BHP Team Risk. <http://humanresearchroadmap.nasa.gov/Evidence/>

Additionally, it is well known that performance changes depending on the levels of stress experienced by an individual. At low levels of stress, performance might be poor, but as stress increases gradually, performance improves. At a certain point, stress level is optimal for performance on a given task. Beyond that optimal level of stress, additional stress might degrade performance, and when stress becomes extreme, the individual might "choke" or panic (Staal, Bolton, Yaroush, & Bourne, 2008). Stress management training (SMT), also referred to as Stress Inoculation Training can result in the building of resilience to stress, and thereby increasing the upper end of the range of stress under which people can perform optimally (Meichenbaum, 2007). SMT programs include a range of training including relaxation techniques, cognitive restructuring, and behavioral skills. Currently a computer-based SMT program, which has proven effective in stressed but otherwise healthy graduate students, is being tested for effectiveness in Flight Controllers at NASA Johnson Space Center (JSC) (Rose, et al. 2013). Additional work is underway to evaluate behavioral and biological markers of resilience to stress in astronauts and astronaut-like populations. Further discussion of stress in the context of cognitive and behavioral health is discussed in the Evidence Book chapter for the BHP Bmed Risk. <http://humanresearchroadmap.nasa.gov/Evidence/>

Of consideration is, however, that while a certain level of stress can optimize performance, factors such as sleep loss, circadian misalignment and work overload have been shown to negatively affect performance. As an example, Healy, Kole, Buck, Gengler & Bourne (2004) demonstrated that continuous time on task leads to faster but less accurate performance. Similarly, Wolfe, Horowitz, Cade, and Czeisler (2000) found that sleep deprivation led to an increase in errors on a visual search task for a target among varying numbers of distractors, as well as to a reduction in the slope of the function relating response time to the number of distractors (see also Horowitz, Cade, Wolfe, & Czeisler, 2003). Thus, sleepy observers responded quickly but carelessly. Evidence has shown however that while objective tests detect deficits caused by sleep deprivation, people are often subjectively unaware of these performance impacts, deciding that they are able to "adapt" to chronically reduced sleep (VanDongen, Maislin, Mullington, & Dinges, 2003). People are similarly unaware of cognitive performance deficits when under the influence of alcohol or drugs, or when experiencing low blood glucose levels (e.g., Barshi and Feldman, 2013). Training can be used to help promote self-awareness and to help individuals become more cognizant of the support they can provide to other crew members under conditions of sleep deprivation. Fatigue-related contributing factors are further discussed in the Evidence Book chapter for the Sleep, Circadian and Workload Risk. <http://humanresearchroadmap.nasa.gov/Evidence/>

Dependencies with ExMC

The ExMC Element develops medical technologies for in-flight diagnosis and treatment as well as data systems to protect patients' private medical data, aid in the diagnosis of medical conditions, and act as repositories of information about relevant NASA life science experiments. Providing capabilities that overcome the challenges of diagnosing and treating injuries or diseases without access to an emergency room and with limited communications with ground-based personnel for consultation and diagnostic assistance will require new health care systems, procedures, and technologies to ensure the safety and success of exploration missions.

Current training paradigms for spaceflight missions assume the ability to quickly evacuate a crew member for return to the ground or assume real-time communication for emergency support from medical personnel on the ground. These assumptions do not apply to Exploration Class missions. Crew medical officers (CMOs) will need to be trained to perform emergency medical procedures autonomously, or in the best case with delayed ground communication, and CMOs will need to maintain these skills throughout the entire mission. IN addition, CMOs will have to perform routine and non-routine medical and dental procedures, including some that may not be anticipated in advance. ExMC has conducted some research on training methods and paradigms for initial, proficiency, and just-in-time training to determine optimal training methods for in-flight medical conditions, and documented their findings in a preliminary white paper report. The ExMC Element Scientist will continue to work with SHFH training researchers to expand and continuously update the research on medical.

Dependencies with HHC

The HHC Element is responsible for understanding the normal physiologic effects of spaceflight and developing countermeasures to those with detrimental effects on human health and performance. (NASA uses the term "countermeasures" to describe the procedures, medications, devices, and other strategies that help keep astronauts healthy and productive during space travel and return to Earth.) HHC provides the biomedical expertise for the development and assessment of medical standards, vehicle and spacesuit requirements and countermeasures that ensure crew health during all phases of flight. Pre-flight countermeasures involve physical fitness and exercise and physiologic adaptation training. In-flight countermeasures include nutritional health, physical fitness, pharmaceuticals and sensory-motor training protocols. Post-flight countermeasures target rehabilitation strategies. The training risk will provide HHC with its findings to inform the training designed for the pre-flight and in-flight countermeasures identified by the HHC risk.

Dependencies within SHFH

The human-computer interaction (HCI) risk in the SHFH Element encompasses all the methods by which humans and computer-based systems communicate, share information, and accomplish tasks. When HCI is poorly designed, crews have difficulty entering, navigating, accessing, and understanding information. The training risk interacts with HCI in two important ways: 1) systems with poor HCI design may be non-intuitive, and require extensive training, and 2) the adequacy of CBT systems depends heavily on the design of the HCI.

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The Mission, Process and Task Design in SHFH Element relates to the definition and development of mission tasks, task flows, schedules, and procedures. In order to provide adequate task design, we need to understand relevant human capabilities and limitations for performing tasks and how these may degrade on long-duration missions. We also need to understand the effect that other factors may have on the human-system performance (e.g., the introduction of automation). The training risk interacts with the task risk in that training determines whether procedural knowledge will be adequate during the performance of a task. The research on training retention, skill transfer, and new training paradigms as well as the training research on matching between task and learning and memory abilities informs the task risk.

D. Levels of Evidence

HRP has established four Categories to describe Levels of Evidence, as shown below:

- Evidence Category I: At least one randomized, controlled trial.
- Evidence Category II: At least one controlled study without randomization, including cohort, case-control, or subject operating as own control.
- Evidence Category III: Non-experimental observations or comparative, correlation, and case or case-series studies.
- Evidence Category IV: Expert committee reports or opinions of respected authorities based on clinical experiences, bench research, or “first principles.”

Evidence for the Risk of Performance Errors Due to Training Deficiencies encompasses lessons learned from 50 years of spaceflight experience, aviation, and ground-based research. A large majority of the evidence comes from space and flight crew reports and accident investigation reports. As these include summaries of subjective experience, expert opinions, and non-experimental observations, they are classified as Evidence Categories III and IV.

Much of the evidence comes from aviation research and accident reports because the number of commercial, military, and private flights each year far exceeds the number of spaceflights. It should be noted that some evidence in this chapter is derived from the Flight Crew Integration (FCI) ISS Crew Comments Database. Although summaries of ISS crew feedback are presented as evidence, the database is protected and is not publicly available, due to the sensitive nature of the raw crew data it contains.

IV. Evidence

A. Spaceflight Evidence

1. Contributing Factor 1: Organizational Training Issues/Programs

Since the beginning of manned space flight, there have been incidents with devastating or near-devastating consequences. One such example is the Mir-Progress collision on June 25, 1997, in which the arriving Russian spacecraft Progress 234 collided with the Spektr module of the Mir space station, causing Spektr's pressure hull to rupture, leaving the crew in a spinning space station without power or computer control, and nearly causing the Mir to be abandoned (Ellis, 2000; Shayler, 2000). Multiple causal factors contributed to the Mir-Progress collision (Ellis, 2000); one of the causal factors of this event resulting in a near-catastrophe was the training-performance interval. Performance declines are associated with increasing intervals between training and performance, and the crew last received formal training four months before the docking incident. Such skill degradation is likely to be exacerbated as mission duration increases, and crews place greater reliance on onboard automation.

While we fortunately have not encountered such a near disaster on ISS, we have still never conducted controlled research in space to assess the risk of performance errors due to training deficiencies nor to determine if there are additional factors unique to the space environment that affect training retention and trained task performance. Additionally, although training issues are covered in crew debriefs, systematic data on effectiveness of training are not collected or analyzed¹. Thus, performance in spaceflight is not specifically assessed to validate current training practices. Skill-based training approaches have not been researched, and schedules for refresher training are not established; adaptive training technologies and delivery systems for onboard training have not been developed.

Nonetheless, concerns about training issues continue to be raised in debriefings of crews returning from space missions. Crew members consistently comment that they do not remember details of ground training; they often comment that they do not recall being trained on specific hardware or payloads, they don't remember specific briefings, and/or they have a hard time remembering training that was at times over two years prior. (FCI ISS Crew Comments Database) For example, interviews with crew members who have served as CMO indicate that following initial training, there are no formal reviews of the entire course if/when they are assigned to another mission, and that there is no formal assessment of the effectiveness of current CMO training and onboard refresher training modules for long-term retention of space medical training. It's possible that such deficiencies are the result of underestimating the importance of training due to the history of low frequency of medical events in space, and a certain comfort

¹ Furthermore, crew performance during training is not always measured objectively, and training records are extremely limited. Thus, systematically assessing training effectiveness is impossible under the current paradigm.

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level due to ground medical expertise always being available when needed. However, that will not be the case with future, long-duration space missions.

Similarly, minimal to no influence of current understanding of human learning, skill acquisition and retention can be seen in “just-in-time” training for new experiments sent to ISS. For example, refresher training for the Dust and Aerosol Measurement Feasibility Test (DAFT) experiment was uplinked to ISS on February 3rd, 2005; it consisted of only three PowerPoint slides, each with a few bullet points, one slide with two pictures of relevant equipment, and one slide of the general process flow chart. Multiple challenges arose, leading to the premature termination of the protocol (see, e.g., Evans et al. 2009; Urban et al. 2005). Such training will not be adequate to support long-duration missions where many potential tasks cannot be predicted and trained in advance, and where ground support may not be immediately available. As evidence, Just-in-time training has moved beyond power point presentations, and there are now just-in-time training videos embedded in certain payload and hardware procedures. In general, the crew is very complementary of these videos in debriefs. However, crew members have also commented that the implementation is inconsistent, such that some videos are much more effective in assisting with task performance than others. (FCI ISS Crew Comments Database)

Another current paradigm of Station operations that compensates for training deficiencies that will not apply to Exploration Class missions is the concept of on-board handover. New crew members arriving to the Station are assigned formal handover time so that experienced crew members can familiarize them with the vehicle and general onboard operations. Additionally, the first time a new crew member performs certain tasks such as using the exercise equipment, using the waste and hygiene compartment, or taking water out of a portable water dispenser, an experienced crew member is often scheduled to provide a functional handover of the task. Crew members have commented that in certain instances they have considered the assistance by an experienced crew member to be “critical” to their performing the task correctly the first time. (FCI ISS Crew Comments Database) It is not likely that there will be experienced crew members who can provide onboard assistance to novice astronauts during Exploration Class missions. Thus, crew members will not have the benefit of such a handover and will have to be trained in advance to perform all such tasks.

In addition to support by fellow experienced crew members, current Station training also assumes that crew members will have ground support for more complex operations, such as for ultrasound imaging. According to a study by Kirkpatrick et al. (2013) on trans-Atlantic remote mentored ultrasound that included NASA medical operations remote guiders, ultrasound imaging is very “user-dependent, a characteristic that has prompted the development of remote guidance techniques, wherein remote experts guide distant users through the use of information technologies.” In crew debriefs, crew members have commented that such remote guidance was needed despite having received pre-flight ground training on ultrasound techniques (FCI ISS Crew Comments Database); additionally, crew members have suggested that for Exploration Class missions either a software solution or training solution should be considered, because the crew would not have a remote guider. Such training and performance support tools do not currently exist and will need to be developed, once a comprehensive assessment has been done to determine the tasks that will require them.

Furthermore, given the stress and problems associated with current training practices for the individual crew members and their families² (Crew members often comment that the missions themselves are far easier on everybody than the years of training), short, efficient, and effective training is needed to support our crews. Station training is being redesigned to reduce the length of the flight assigned crew flow; however, research and development is required to maximize training coherence for effective retention and transfer. Additionally, skill-based training must replace task-based rehearsal to support generalizability and the ability to deal with unexpected, untrained-for emerging tasks and opportunities. Crews must develop appropriate responses and procedures as situations demand, drawing upon in-depth understanding of spacecraft systems and operations. Extensive cross training will also enhance situational resiliency.



Figure 1 (left). Photo JSC2010-E-107015 Courtesy of NASA. ISS crew members Satoshi Furukawa, Mike Fossum, and Sergey Volkov train on cardiopulmonary resuscitation (CPR) in a 1-G ground training facility, pushing down onto a dummy strapped onto the crew medical restraint system (CMRS), the gold-colored platform. **Figure 2** (right). Photo ISS034-E-005260 Courtesy of NASA. ISS crew member Oleg Novitskiy demonstrates one method of performing CPR in 0-G onboard the ISS by pushing off the ceiling with his feet and down onto the CMRS.

Training that aims at the acquisition of durable skills often leads to high specificity (see, e.g., Healy and Bourne, 1995; Vogel and Thompson, 1995). In other words, skills that are well retained over extended periods of time do not generalize well beyond the specific context within which they were trained. Thus, because it will not be possible to train, or even anticipate, all

² The current training regime is very stressful for crew members and their families as it involves many years of intensive and intense work, frequent overseas travel, and long absences from home.

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potential tasks, current task-based training can be less than adequate to meet all mission objectives. Furthermore, simulated environments and ground-based full-scale models or mockups cannot be completely representative of flight conditions. Representing a true 0-G environment on the ground has presented many challenges for training, so current simulations facilities and methods may not be adequate for preflight training. Figures 1 and 2 depict training CPR in a 1-G ground based mockup and demonstration of the trained operation being performed in 0-G onboard the ISS. Figure 2 was tweeted by ESA astronaut Samantha Cristoforetti tweeting that you, “Can’t train that on Earth.” (Cristoforetti, 2014)



Figure 3 (left). *Photo Courtesy of NASA.* The 1-G ground mockup of the Permanent Multipurpose Module (PMM) with stowage placed on the floor and strapped onto one wall. **Figure 4** (right). *Photo ISS034-E-005511 Courtesy of NASA.* ISS crew member Kevin Ford floating in 0-G onboard ISS in the PMM with stowage restrained to all four walls.



Figure 5. *Photo ISS042-E-002467 Courtesy of NASA.* ISS crew member Barry “Butch” Wilmore translating through the ISS with a Jettison Stowage Bag (JSB) à la Superman using a handrail to propel him forward.

Stowage problems on ISS are one example of 1-G training failing to build adequate skills needed for task execution in 0-G. As documented in the FCI ISS Crew Comments Database, a true

representation of the stowage of equipment and materials onboard the ISS is very difficult to achieve on the ground and can create issues for the crew. Stowage mockups in 1-G are limited because gravity restricts operations, translation, and stowage placement in the training facilities. Given the constraints of a 1-G-based translation path, it is not possible or safe to place things where they would potentially be stowed onboard the ISS. On-orbit there is the benefit of weightlessness, which allows stowage of items on any axis with proper restraint (Fig. 3 and 4.) The crew can translate through the available volume and position their bodies to move around obstructions or protrusions in the translation paths (Fig. 5). Additionally, while on-orbit, some of the stowage lockers are packed tightly, making it difficult to re-stow items due to the lack of gravity working against the crew member. Similarly, crews often have trouble with items floating off during retrieval or re-stow. In a 1-G environment, stowage does not behave the same as in a 0-G environment. However, tasks and procedures are written based on what is known from testing in a 1-G environment, and so is the training; unfortunately, a mock-up may not be the best representation of what it will be like for the crew members while on-orbit. Given the gravitational differences between Earth and orbit, and disconnects between ground training and actual life on-orbit, the crew members have a lot to learn once onboard the ISS. The result is that, upon arrival on ISS, the crew often has difficulty managing stowage and operating nominally, leading to loss of precious time, inefficiencies, and crew frustration.

An example in which experience in the working environment (both in space and in Mission Control) led to a successful outcome was Extra-Vehicular Activity (EVA) number 21. EVA21 was a contingency EVA that took place on May 11th, 2013, and involved the replacement of a pump flow control subassembly that was leaking ammonia from the Station's photovoltaic thermal control system. The two performing astronauts were out the Station's hatch for their EVA barely 36 hours following the discovery of the ammonia leak. Without specific task-training and with only bare minimum preparation time, the EVA was a great success. Although system failures similar to the one necessitating EVA21 can be expected on future vehicles, such a success can not be expected on future missions.

The impressive success of EVA21 was unique. The EVA crew relied heavily on their prior EVA experience as an EVA crew, and in particular with the specific worksite and its translation paths. That experience was gained when they flew together on a Shuttle mission, STS-127, 4 years earlier (July, 2009). The ground crew also had specific relevant experiences. The Flight Director for EVA21 was the one who led the planned EVA18 (August, 2012) and the immediately following contingency EVA19. The lead Station Power, Articulation, Thermal, and Analysis (SPARTAN) flight controller, responsible for the relevant system, was involved with EVA18, EVA19, and especially with EVA20 (November, 2012) which dealt with the same system and the same worksite. Their experience was fresh; all 3 prior EVAs were conducted within the previous 9 months. The Capsule Communicator (CapCom) who handled all communication from Mission Control Center with the EVA crew had extensive EVA experience himself and also with the specific worksite. What's more, EVA 21 was guided from the ground, step by step, for the entire duration, as the crew did not have a chance to see the final procedure prior to egress. Without extensive experience, substantial recent involvement in almost identical tasks, and real-time communication with the ground, the success of EVA21 would not have been possible. Crews of Exploration-Class missions will not have the benefit of any of these success ingredients. Their success will depend on their training.

Finally, optimal strategies for training problem solving and decision-making in space operations have not been studied. However, studies done by the SHFH Element Training Risk to support the development of flight controller training in problem solving and decision making demonstrate significant promise (see, e.g., Schmidt, et al. 2011; Martin, et al. 2012).

2. Contributing Factor 2: Matching Between Task and Learning and Memory Abilities

Current training practices for space missions are largely task-based and rely heavily on rehearsal; crew training is not guided by empirically validated principles of skill acquisition, retention and transfer known from studies in the psychology of learning (for an example of a training program that is guided by such principles, see, e.g., Barshi, 2015). Furthermore, there currently is no systematically collected spaceflight evidence for this contributing factor. As mentioned earlier, there is much anecdotal evidence that crew members' learning and memory abilities do not match their tasks (FCI ISS Crew Comments Database).

B. Ground-Based Evidence

1. Contributing Factor 1: Organizational Training Issues/Programs

In a recent study of aviation accidents that happened between 1988 and 2006 (Velazquez, Peck, & Sestak, 2015), training inadequacies were found to be the single largest contributing factor to accidents in which crew error was a causal factor. Training inadequacies were found to be a factor in 48% of the accidents.

As early as 1953, in the early days of human factors research, training had already been recognized as a critical issue. In his seminal work on human factors in air transportation, McFarland (1953) dedicates a whole chapter to training issues. He notes that "little attention has been given to the human factors involving an airman's understanding of his environment and the physical factors influencing his efficiency" (p. 152). More recent works continue to echo the same concerns. Training deficiencies are clearly pointed out in the analysis of accidents and incidents in aviation (e.g., Barshi & Loukopoulos, 2012; Dismukes, Berman, & Loukopoulos, 2007; Loukopoulos, Dismukes, & Barshi, 2009a, 2009b), other modes of transportation (National Transportation Safety Board (NTSB)), and in other high-risk industries (e.g., Grote, 2009; Helmreich, & Meritt, 1998; Reason, 1997).



Figure 6. Fire damage to the fuselage of Asiana Flight 214. (NTSB, 2014)

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An example from commercial aviation is the July 6, 2013, crash of Asiana Flight 214 at the San Francisco airport (Fig. 6). In the NTSB analysis of the crash, the NTSB concluded that "The PF [pilot flying] had an inaccurate understanding of how the Boeing 777 A/P [autopilot] and A/T [autothrottle] systems interact to control airspeed in FLCH SPD [flight level change - speed] mode, what happens when the A/T is overridden and the throttles transition to HOLD in a FLCH SPD descent, and how the A/T automatic engagement feature operates. The PF's faulty mental model of the airplane's automation logic led to his inadvertent deactivation of automatic airspeed control. Both reduced design complexity and improved systems training can help reduce the type of error made by the PF." (NTSB, 2014, p. xii).

With the anticipated increased automation and complexity in future space vehicles, crew members are likely to find themselves in similar situations to that of the Asiana Captain. Like the Asiana Captain, our astronaut crews will have no operational experience with their specific systems, activities, and missions.

Most accidents and incidents involve some loss of situation awareness (SA). Such loss of SA is often cited as causal in aviation accidents as well as in Mission Control Center errors (see, e.g., Endsley & Garland, 2000). Analyses of general aviation accidents that have been caused by the pilot's lack of SA cited inadequate general aviation training that did not effectively address how to improve SA. Analysis was conducted to determine the nature of the problems that occur in situations where SA was lost, as well as the differences in SA between pilots who perform well and those who do not. The results yielded four key recommendations for how SA could be improved through training. The first recommendation is to provide training that will allow the pilots to develop good task management strategies to deal with interruptions, distractions, and overall workload that can pose a high threat to SA. The second recommendation is development of comprehension: providing pilots with the tools necessary to properly gauge the temporal aspects of the situation, the risk levels involved and personal and system capabilities for dealing with the situation. The third recommendation is to provide pilots with skills to project and plan, which will allow them to actively seek important information in advance of a known immediate need for it, and plan for contingencies. The final recommendation is to encourage information seeking and self-checking activities; these are skills that will help pilots notice trends and react to events quickly. Development and implementation of training programs that focus on these four recommendations should effectively improve SA in pilots (Endsley & Garland, 2000).

Performance errors related to training deficiencies are also documented in other high-risk endeavors. In a study by Schaafstal, Schraagen, and van Berlo (2000), Navy weapons engineers' troubleshooting problems were attributed to insufficient training, technical documentation written from an engineering viewpoint instead of a maintenance viewpoint, and a gap between the theoretical knowledge and application of this knowledge in a real-life situation. That gap is a clear training deficiency.

Unlike spaceflight, there is an abundance of ground-based evidence based on controlled studies related to the training risk. However, much of the research literature on training is motivated by current training practices aimed at current training needs. There is no experience with long-duration space missions where crews must practice semi-autonomous operations, where ground support must accommodate significant communication delays, and where so little is known about the environment. Thus, not only must we resolve known deficiencies in the current state-of-the-

art in training, we must also develop robust methodologies and tools to prepare our crews for the unknown. The research necessary to support such an endeavor does not currently exist, but existing research does reveal general challenges that are relevant to long-duration, high-autonomy missions.

For example, learning is highly specific to the conditions under which it occurred, especially when the learning involves procedural, as opposed to declarative, information. To account for this specificity, Healy and Bourne (1995a; see also Healy, 2007; Healy, Wohldmann, & Bourne, 2005) proposed a procedural reinstatement principle, according to which training on one skill does not transfer to another related skill unless the procedures required by the two skills overlap. This principle is clearly related to other principles and theories in the literature, including: Thorndike's (1906) theory of identical elements (see also Rickard & Bourne, 1995, 1996; Singley & Anderson, 1989); Tulving and Thomson's (1973) encoding specificity principle; Morris, Bransford, and Franks's (1977) transfer-appropriate processing principle (see also McDaniel, Friedman, & Bourne, 1978; Roediger, Weldon, & Challis, 1989); Proteau, Marteniuk, and Lévesque's (1992) specificity of practice theory involving sensorimotor representations for motor learning; and Kolers and Roediger's (1984) theory involving procedures of the mind. These empirically driven principles and theories inform our current research as we develop ways to apply their implications and ramifications to our training programs design (Barshi, 2015).

Performance declines, exhibited by increased response time (or decreased accuracy), have been known since the time of Ebbinghaus (1885/1913), who used a measure of savings (i.e., the amount of relearning required to achieve the criterion level of performance during original learning). Subsequently, this relationship between response time and retention interval was described as a power law (Wickelgren, 1974), $R = d + fT^g$, where R is response time, T is the retention interval, d is the criterion of original learning, f is a scaling parameter, and g is the rate of forgetting. This Power Law of Forgetting (Wixted & Carpenter, 2007; see also Rubin & Wenzel, 1996) can be thought of as the inverse of the Power Law of Practice (Newell & Rosenbloom, 1981), which describes the acquisition process for most skills (the relationship between trials of practice and time to make a correct response is a power function, $R = aN^b$, where R is response time on trial N , a is response time on trial 1, and b is the rate of change). The understanding of these relationships is crucial for the design of effective training.

Even with effective initial training, long periods of disuse lead to skill decay (see, e.g., Winfred, et al. 1998). The passage of time and the lack of opportunity to rehearse or refresh acquired knowledge or skills will result in performance decrements due to forgetting what was learned. Training programs that do not account for degradation of learned skills or knowledge (e.g., by including refresher training or by providing just-in-time training rather than advanced training on the ground) may result in inferior task performance. In addition, fragile memory structures crumble under stress and fatigue (see, e.g., Staal, 2004). Thus, training for long-duration missions must be robust, and must support extensive memory structures that can withstand the effects of fatigue and stress likely to be experienced during such missions. Because rote learning leads to fragile memory structures, training for long-duration missions will have to take a different approach. Thus, onboard refresher training as well as just-in-time training and performance support tools must be developed to support long-duration missions. Research must be conducted to determine the sensitivity of different skills to disuse, and the refresher schedule required. Furthermore, to support long-duration missions we must develop an understanding of

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the kinds of tasks that must be trained in advance, those that can be trained enroute, and those that can be trained just-in-time or even supported while being performed without prior training.

More generally, whether or not the correct training methods, materials, and platforms are available, qualified instructors and valid evaluation methods are also needed to ensure adequate training. Given that methods, materials, and platforms are still in development for long-duration mission concepts, it may be problematic to find or train instructors in order to promptly and properly support training programs for such future missions. However, the benefits of developing and validating systematic approaches to training skills and transfer of skill between situations far outweigh the potential costs and consequences of not being able to perform tasks on missions with high crew autonomy. Furthermore, developing guidelines for adequate distribution of training topics across the full continuum of training opportunities (from initial pre-mission training, through ground and in flight refreshers, to onboard initial training, to just-in-time training, and all the way to performance support tools) will substantially increase training efficiency and effectiveness. Determining the proper methodologies to support such distribution will mitigate further risk posed by current practices. Assuring these benefits of new training approaches requires research.

Task-based training does not necessarily lead to the development of generalizable skills (see, e.g., Healy and Bourne, 1995). Thus, training that is based on specific tasks might fail crew members faced with unexpected new emerging tasks. Because not all tasks on a long-duration mission can be anticipated, training should focus instead on generalizable skills. Although we know that this needs to be done, we don't yet know how to do it. Research is required to develop appropriate generalizable skill-based training.

A further complication arises as a result of the novel technologies and operational scenarios that will exist for deep-space missions. Extensive automated and robotic systems may be used to assist crew in their work. Given that these technologies are still emerging, it is likely that modeling and simulation platforms that can be leveraged for training on such systems will be limited or lacking. Even well-designed systems that address the right problem can produce accidents if humans do not understand what the automation/robot is doing or how control is distributed between human and automation/robot. Even experienced, skilled, and motivated users might make an error if training does not provide a complete and accurate model of the automation and human-automation integration, or if direct "hands-on" training with the system (or a simulation of the system) is not available. Training must align the user's mental model of the automated or robotic operations with how the automation/robot is designed to function (see, e.g., Billings, 1997). This includes teaching specific procedures, instilling in trainees an understanding of the environment and work to be done, and communicating a deep functional understanding of the automated systems. Training should also include information about how control is distributed between user and automation, how the user may change control, what other factors influence control state, and how to determine the current state of control. Some applications may require training for supervisors of automation or robotic behavior, not just operators.

Clearly, more research is necessary to disentangle the various relevant issues so that specific training recommendations can be used to guide organizational training program.

2. Contributing Factor 2: Matching Between Task and Learning and Memory Abilities

Matching between task and learning and memory is a factor when the individual's relative efficiency with which new information is acquired and relatively permanent adjustments made in behavior or thinking, are not consistent with mission demands. Task design is often driven by the constraints of the technology involved. When the constraints of the human operator and those of the operational environment are not taken fully into account, problems arise. Furthermore, when training is designed strictly to meet performance criteria at the end of training, long-term retention is compromised (Healy and Bourne, 1995). Thus, when training is focused on a task that is technologically driven and is only aimed to "pass the class," trainees' ability to perform adequately following a long retention interval is greatly reduced increasing the risk of error and of compromising mission objectives.

Research has shown that training aimed at long-term retention often results in high specificity, and thus low generalizability (e.g., Vogel and Thompson, 1995). Specificity might be desired when all tasks are well known and understood in advance; that, however, cannot be the case for future long-duration space missions. If anything, we know that our crews will face situations and tasks we do not currently have the tools or the ability to foresee. As a result, future training should focus on generalizability of skills, rather than specificity. Current research has made important, albeit small, steps towards understanding generalizability, but we are still far from having a clear methodology for effective training of generalizable skills (e.g., Healy and Bourne, 2012).

One small example of the issues associated with this contributing factor has to do with the differences in the cognitive mechanisms underlying recognition and recall. The difference between recognition and recall was identified in the early days of psychological research (e.g., MacDougall, 1904); studies have shown that it is much easier to recognize than to recall. As MacDougall (1904) describes: "the name which cannot, by the greatest racking of memory, be brought back to consciousness is thus uttered spontaneously and without hesitation when the bearer is again met face to face" (p. 229). Similarly, when a task involves the manipulation of an interface and contains a sequence of several steps, an operator can master that sequence through practice during training, by recognizing the correct buttons to push or switches to set. However, following a retention interval of disuse, as would be expected with many tasks during a long-duration space mission, the operator now has to recall those steps in the correct sequence, and no longer has the advantage of simply recognizing them. The memory structures constructed during training are thus critical to performance. Such memory structures can be very fragile and vulnerable to forgetting (see, e.g., Barshi & Loukopoulos, 2012; Loukopoulos, Dismukes, & Barshi, 2009a), even when the operator is an expert performer with extensive experience in the domain (see, e.g., Dismukes, Berman, & Loukopoulos, 2007). Hence, training that isn't sensitive to the potential mismatch between task demands and the operator's learning and memory constraints can lead to increases in the risk of error and of compromising mission objectives.

V. Computer-Based Modeling and Simulation

Understanding and predicting human-system performance and identifying risks that may be inherent in a concept or a design is often achieved via computer-based modeling or simulation.

The use of human performance models can result in significant lifecycle cost savings as compared to repeated human-in-the-loop evaluations, but accurately modeling the human is extremely difficult. In the SHFH domain, modeling and human-in-the-loop evaluations must be used in concert. We do not have high-fidelity human performance models, and most of those existing models have not been sufficiently validated or certified. Accordingly, models must be used in a limited fashion – i.e., to help determine the critical areas that should be addressed through the more costly, but more representative human-in-the-loop evaluations. As mentioned above, modeling and simulation platforms can be leveraged for training on emerging technologies that are still in development.

VI. Risk in Context of Exploration Mission Operational Scenarios

In addition to the problems that arise when training programs are inadequate or unavailable, training for Exploration Class missions bring new challenges and risks. The aviation industry, military, and even NASA, have all had the luxury of designing training programs with the valid assumption that personnel can be quickly returned to the training environment for additional training, that freshly trained personnel can quickly replace existing personnel, and/or that personnel in the field of operations can be supported real-time by support personnel. These assumptions are no longer valid when considering the mission architectures proposed for NASA's long-duration, Exploration Class missions.

Future Exploration-mission scenarios will increase in duration and in distance from earth. This increase will require developing new technologies, new work methods, and new ways of ensuring that these novel elements are suitably integrated. This development must include the design and application of proper training methodologies both on the ground in preparation for missions and while in space. Missions carried out in space will need greater flexibility and less dependence on ground support, and new interaction between ground-based resources and crew will also be needed and require increased pre-flight and onboard training. Risks from inadequate design of human-technology interaction will increase as mission requirements become more demanding and as missions are carried out in unfamiliar circumstances substantially different from our experience base. Human factors principles will need to be extended and applied to design for common and effective human-system interaction/interface design in terms of usability, operability, maintainability and trainability to reduce risk.

VII. Gaps

Given the current DRMs involving surface operations on a planetary body which require significant time in transit to and from that body, it is natural to expect that transit time be used, at least in part, for training. However, we do not have validated effective on-board training methods and tools. We do not yet know which training topics are best trained pre-mission and which can be trained during transit. Moreover, training is likely to be limited to an immersive virtual environment during transit, constraining, in turn, the scope and efficiency of such training. Regardless, transit time could indeed be used for training, but the potential for human error, complication of the new systems, and the novelty of the mission and activities for crew and

ground support will substantially compound the risk. Additionally, we cannot know all of the tasks crew will have to perform onboard or during surface operations, so training will need to be skill-based rather than task-based. Unfortunately, we do not know the types of skills and knowledge that can be generalized across tasks. Therefore, current gaps in our knowledge of training include, but are not limited to:

- We do not know the types of skills and knowledge that can be retained and generalized across tasks for a given mission to maximize crew performance.
- We need to identify effective methods and tools that can be used to train for long-duration, long-distance space missions.
- We do not know which validated objective measures of operator proficiency and of training effectiveness should be used for future long-duration exploration missions.
- We need to develop guidelines for effective onboard training systems that provide training traditionally assumed for pre-flight.

These training gaps need to be coordinated with current and emergent gaps in other SHFH Risks (e.g., Risk of Inadequate Design of Human and Automation/Robotic Integration, Risk of Inadequate Human-Computer Interaction, and Risk of Inadequate Mission Planning and Task Design) and HRP Elements (e.g., BHP's Risk of Performance Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team, and Exploration Medicine and ExMC). As NASA turns toward longer duration missions beyond low-earth orbit, challenges associated with communication latencies and skill degradation will require cross-disciplinary solutions.

A summary of all SHFH gaps can be found in the Human Research Roadmap at <http://humanresearchroadmap.nasa.gov/>.

VIII. Conclusion

The evidence presented in this report describes issues related to the risk of performance errors due to training deficiencies. Contributing factors regarding training deficiencies may pertain to organizational processes and training programs for spaceflight. For instance, when training programs are inadequate in design or implementation (e.g. inappropriate or missing content, improper timing of training, poor or missing intervals of refresher training, or inappropriate delivery methods including training in a different gravity field or different environment than the task requires) or when training programs are unavailable (e.g. unplanned need for onboard training in response to an unexpected hardware malfunction, injury to a crew member, or change in mission). Furthermore, matching between task and learning and memory abilities is a contributing factor when the individual's relative efficiency with which new information is acquired, and relatively permanent adjustments made in behavior or thinking, are inconsistent with mission demands. Thus, if training deficiencies are present, the likelihood of errors or of the inability to successfully complete a task increases. What's more, the overall risk to the crew, the vehicle, and the mission increases.

Substantial evidence supports the claim that inadequate training leads to performance errors. Barshi and Loukopoulos (2012) demonstrate that even a task as carefully developed and refined over many years as operating an aircraft can be significantly improved by a systematic analysis, followed by improved procedures and improved training (see also Loukopoulos, Dismukes, & Barshi, 2009a). Unfortunately, such a systematic analysis of training needs rarely occurs during the preliminary design phase, when modifications are most feasible. Although operational tasks are executed in mockups and simulators by spaceflight crews during preflight training, and feedback regarding interfaces, tasks, and operations is received, often hardware, system and software designs are relatively mature. Therefore, it is often cost prohibitive to modify design based on feedback from training. Hence, designers must consider training when designing hardware and software with crew interfaces, procedures, and operations. Unfortunately, training is often seen as a way to compensate for deficiencies in task and system design, which in turn increases the training load. As a result, task performance often suffers, and with it, the operators and the mission. On the other hand, effective training can indeed compensate for such design deficiencies, and can even go beyond to compensate for our lack of knowledge or for failures of our imagination to anticipate all that might be needed when we send our crew members to go where no one else has gone before. Thus, conducting training research to design effective training, determining effective and efficient ways to implement research findings in training programs, and incorporating training considerations in system design can go a long way towards mitigating mission risks.

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XI. List of Acronyms

A/P	Autopilot
A/T	Autothrottle
BHP	Behavioral Health and Performance
CapCom	Capsule Communicator
CBT	Computer Based Training
CMO	Crew Medical Officer
CMRS	Crew Medical Restraint System
CPR	Cardiopulmonary Resuscitation
DAFT	Dust and Aerosol Measurement Feasibility Test
DoD	Department of Defense
DRM	Design Reference Mission
ExMC	Exploration Medical Capability
EVA	Extra-Vehicular Activity
FCI	Flight Crew Integration
FLECH SPD	Flight Level Change - Speed
G	gravity
HARI	Human and Automation / Robotic Integration
HCI	Human-Computer Interaction
HFACS	Human Factors Analysis and Classification System
HHC	Human Health Countermeasures
HRP	Human Research Program
HSID	Human-System Interaction Design
HSRB	Human System Risk Board
ISS	International Space Station
JSB	Jettison Stowage Bag
JSC	Johnson Space Center
LEO	Low Earth Orbit
MPTASK	Mission, Process and Task Design
NASA	National Aeronautics and Space Administration
NEA	Near Earth Asteroid
NEO	Near Earth Object
NTSB	National Transportation Safety Board
PF	Pilot Flying
PMM	Permanent Multipurpose Module
PRD	Program Requirements Document
SA	Situation Awareness
SFRM	Spaceflight Resource Management
SHFH	Space Human Factors and Habitability
SHFE	Space Human Factors and Engineering
SMT	Stress Management Training
SPARTAN	Station Power, Articulation, Thermal and Analysis
TDT	Team Dimensional Training